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Taking advantage of open data in coastal science and conservation

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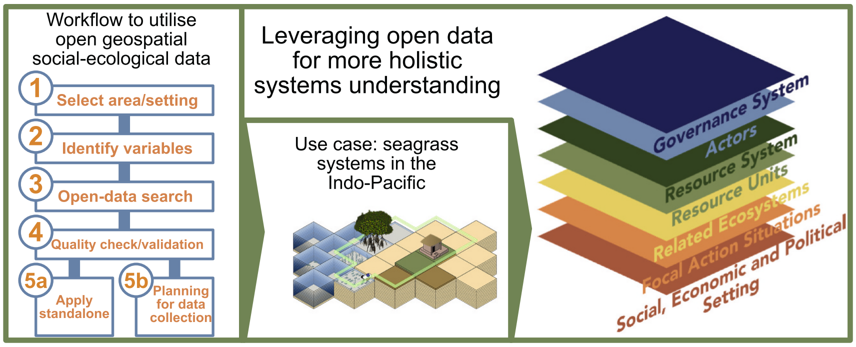
HIGHLIGHTS

- There now exist vast quantities of open ecological and societal data that are relevant to coastal research and management.
- Finding and accessing these data comes can be challenging without specialized training.
- We propose a workflow to formalize the search for open data to support social ecological system research and management.
- An example using seagrass systems in the Indo-Pacific is presented to guide others in applying this workflow.

GRAPHICAL ABSTRACT



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ABSTRACT

Human society relies on, and interacts with, a diverse assortment of organisms and ecological systems, from the local to the global level. Research and management of these coupled social-ecological systems requires data that speaks to the variety of processes, statuses, and situations defined by them. Effective stewardship is enhanced by interdisciplinary thinking and, critically, access to interoperable data describing human society and governance and ecological and environmental conditions. Such approaches are inherently challenging, especially for those without broad training. In this paper, we propose a workflow harnessing the Social-Ecological System Framework to identify, access, and utilize geospatial data from across a spectrum of social and ecological indicators. We demonstrate the application of this workflow using Tropical Indo-Pacific seagrasses as an example system and in doing so, demonstrate the wealth of available open-data which can support an enhanced understanding of social-ecological system dynamics. With this workflow, we provide a readily applicable tool for use by coastal researchers and managers to support more inclusive social-ecological decision making.

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1. Introduction

> "We are drowning in information, while starving for wisdom. The world henceforth will be run by synthesizers, people able to put together the right information at the right time, think critically about it, and make important choices wisely."
>
> E. O. Wilson, Consilience: The Unity of Knowledge (1998), p. 294

Coastal systems exist at the complex interface between land and sea and are influenced by numerous natural and anthropogenic forces of both marine and terrestrial origin (Halpern et al., 2007; Tallis et al., 2008). These environments are typically characterized by mosaics of habitats—including coral or oyster reefs, mangroves, salt marshes, and seagrass meadows—inhabited by a diversity of organisms that provide critical ecosystem services upon which humanity depends (Barbier et al., 2011; Selig et al., 2019; Friess et al., 2020; Heckwolf et al., 2021). This interface is also where people and nature are concentrated, with approximately 2.15 of Earth's eight billion people living near the coast (Reimann et al., 2023), a number that is expected to increase into the future (Merkens et al., 2016). As a result, coastal systems have been–and will be–extensively impacted by changing human activities across regions, often with negative repercussions for both nature and society (Thomas et al., 2017; Ning et al., 2018; Kennish, 2021; Smith et al., 2021; Irrgang et al., 2022).

Effective and equitable management of coastal systems is imperative for sustainable provision of ecosystem services for current and future generations (Bennett, 2018). This goal foremost requires an understanding of the past and current status of these systems, how they are maintained and utilized by ecological and human communities, and how they respond to external drivers, including feedbacks between coastal systems and human societies (Sala et al., 2021). Coastal research has historically focused on anthropogenic drivers of change in nearshore systems, and less on how the diversity of uses—and users—can be sustained in the face of growing and various threats (Kittinger et al., 2012; Calderisi et al., 2021). Moreover, underrepresented and marginalized groups have often been excluded in these assessments, despite their often higher reliance on coastal services and greater vulnerability in the face of global change (Cinner et al., 2012; Habib et al., 2024; Atindana et al., 2025).

Social-ecological systems (SES) thinking aids in considering conservation within what Mace (2014) describes as a "people and nature" framework, alluding to human society as inherently integrated with the ecological system. This framework necessitates both the integration of social sciences within coastal and marine research and management (Popova et al., 2023). To facilitate this, robust and relevant data are essential to comprehend historical and contemporary changes in ecosystem health, societal impacts, and desired outcomes, and to be able to adapt to future change. Most surveys of coastal systems primarily collect ecological (e.g., species diversity/abundance, biomass), physical (e.g., sea surface temperature, salinity, dissolved oxygen) and chemical (e.g. nutrients) data, which is costly, time-consuming and requires specialist skills, materials and/or infrastructures. Coincident data on human dimensions (e.g., demographics, governance structures, etc.) compounds these costs and skill requirements while posing additional challenges to properly integrating these data streams at the appropriate spatial and temporal scales. While there is no substitute for data that are "fit-to-purpose" for a given objective, the increasing availability, utility, and diversity of open-access, geospatial data can be co-opted to increase the scope and relevance of investigations into coastal systems (e.g. McLaughlin et al., 2002).

The proliferation of existing datasets, coupled with advancing technologies for data integration and analysis, has necessitated guiding principles to maintain data standards and responsible use (Manzano and Julier, 2021). The Findable, Accessible, Interoperable and Reproducible (FAIR) principle (Wilkinson et al., 2016) serves as a benchmark for dataset availability and utility across various applications. For marine and coastal geospatial data, numerous portals provide FAIR data at various spatiotemporal scales and resolutions, such as Copernicus climate (https://climate.copernicus.eu) and marine (https://marine.copernicus.eu) services, the European Space Agency (ESA) earth online (https://earth.esa.int/eogateway/catalog), and the National Aeronautics and Space Administration (NASA) earth data (https://www.earthdata.nasa.gov) portals. Regional portals like the Western Indian Ocean (WIO) Symphony (https://symphony.nairobiconvention.org; WIO Symphony, 2022) and the Marine and Coastal Operations for Southern Africa and the Indian Ocean (MarCOSIO; https://marcosio.org; Sibolla et al., 2023) also offer regional data with a broader range of indicators, including human dimensions. With the availability of high-resolution datasets, there is an increasing opportunity to investigate human interactions with coastal environments, particularly in semi- or highly-developed seascapes (Mod et al., 2016).

Integrating the study of coastal ecosystems is a difficult challenge, as investigators must be careful to responsibly select and apply datasets. Numerous tools and frameworks exist to aid in the analysis of integrated SES (Binder et al., 2013). One of the most widely used frameworks, the Social-Ecological System Framework (SESF), was proposed by Ostrom (2007) to address complex social-ecological problems, such as over-harvesting of resources, as well as to provide a common framework whereby scholars can communicate on critical system characteristics across disciplinary divides (Ostrom, 2007, 2009; McGinnis and Ostrom, 2014). The SESF is a tool that helps researchers focus their methodologies and organise and use SES data (Nagel and Partelow, 2022). It has been argued that the SESF, developed primarily from a social science perspective, has limited options for ecological integration due to a restricted range of available variables, often relying on secondary ecological data sources (Nagel and Partelow, 2022). Indeed, past SESF studies have frequently leveraged primarily or even exclusively social variables, shifting emphasis away from key concept of a coupled system (Rissman and Gillon, 2017; Guerrero et al., 2018). It appears, then, that there remains an ongoing challenge in integrating both ecological and social dimensions into SES approaches. However, the open-data revolution may provide opportunities to support such approaches, through the availability of ecological and social pre-processed data.

In this paper, we set out to explore the opportunities provided by open data to support SES perspectives on coastal systems. We aim to showcase the potential and availability of multidisciplinary, open geospatial data in coastal science, monitoring and conservation. To do this, we present a workflow that can support and add value to the planning of fieldwork and/or conducting research or monitoring. The aim is that this workflow will support users towards a more holistic understanding of coastal environments and an integration of ecological and social datasets for addressing real-world conservation and management issues.

The workflow consists of five components: 1) selection of the setting; 2) identification of potential variables; 3) search for open-data sources; 4) quality checking; and 5) use of the acquired dataset along with any existing data or planning for additional primary data collection. We provide a general description, and rationale, for each component in the workflow. The workflow incorporates Ostrom's SESF to aid in the identification of potential internal and external variables affecting the system of interest, with the aim of promoting a holistic application of coastal science that includes an explicit human dimension. We then provide an example application framed around the Indo-Pacific Seagrass bioregion (Short et al., 2007). Our aim is to demonstrate how easily the workflow can be applied to a real-world system, but note that the workflow could readily be applied to any coastal system for which data exist.

2. Materials and methods

2.1. The workflow

We developed a workflow for identifying open-access, geospatial, social-ecological, data for use across multiple applications (Fig. 1). We use the SESF to guide the selection of relevant variables towards the formal search for data that can be readily applied to research questions and for inclusion in monitoring and assessments. We detail five steps with further suggestions on how this can be developed for individual research, monitoring or management applications, using the example of Indo-Pacific seagrass systems. The five steps are: (1) the formulation of questions relevant for research or monitoring, along with the identification or estimation of the boundaries of the system(s) of interest; (2) variable selection from across the SESF; (3) targeted searches for open geospatial data; (4) curation of data; and finally, (5) integration of the acquired dataset towards pre-existing research questions, or planning for future data collection (Fig. 1).

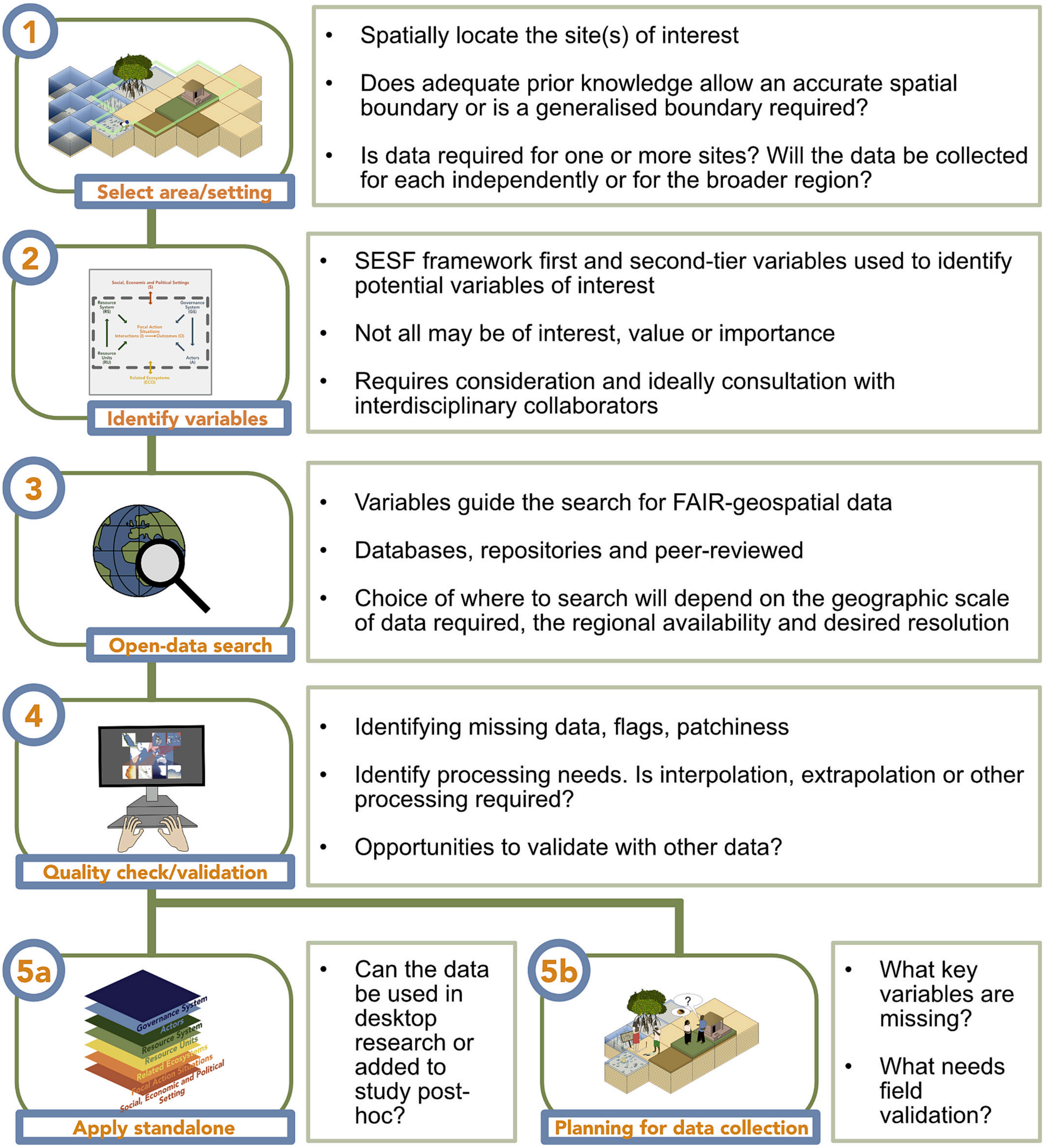

Fig. 1. Schematic of the five-step workflow for searching for open, geospatial, social-ecological data.

3. Results and discussion

3.1. Step 1. Defining questions and system boundaries

Developing questions in advance of any search for data will naturally provide the greatest chance of successfully investigating the SES. The questions may be more or less specific and will depend on the overall aims of the research or monitoring. Knowing what we hope to understand from the system will help us identify the critical variables from the system (see Step 2), and first requires that the study area be well-defined.

Spatial boundaries relate primarily to the physical confines of the system. While the SESF is structured with an assumed geographical boundary (Nagel and Partelow, 2022), defining these spatial limits is challenging for several reasons. First, such boundaries may not always be clearly defined, and further social and ecological boundaries may not map onto one another exactly (e.g., a single habitat spans jurisdictional boundaries) (Nagel and Partelow, 2022). Additionally, it may be difficult to know the scale of influence of different variables or indicators. For example, influences on water quality—and therefore impacts on coastal systems—may arise from watershed changes that happen tens or even hundreds of kilometres away (Lefcheck et al., 2018). Given some megaherbivores can migrate up to 4000 km, conservation strategies for megaherbivores in one region may exasperate management conflicts in other locations (Jones et al., 2022a). Similarly, human use of reefs for fishing may not always correlate with proximity, but rather the ease with which people can access the fishing grounds and the distance to market (Cinner et al., 2013; Quiros et al., 2018). Temporal boundaries also need to be considered. Many situations are highly dynamic and may develop rapidly over time, for example, extreme weather events that occur over short temporal periods yet create significant impacts within the SES. In contrast, management can take years to decades to fully realize, from conception to implementation and enforcement. The setting of boundaries, both spatial and temporal can be revisited after subsequent steps in the workflow. Once data has been identified and retrieved, these boundaries can be adjusted based on an understanding of the scales at which different variables and indicators operate.

While the delineation of proper boundaries may seem challenging or overwhelming at first, the process can be made easier with a well-defined question or line of investigation. Once data has been identified, the spatial delineation of SESs can also be made possible through the identification of overlapping homogenous ecological and socio-economic regions (Martín-López et al., 2017). This process can also be facilitated by drawing on natural geologic boundaries, such as self-contained embayments, on existing management zones, such as an established marine park, and/or on existing schema devised by local, state, or federal agencies. For example, the U.S. Geological Survey has defined hierarchical hydrological units (HUCs) that map onto major features of the watershed and can be aggregated (or disaggregated) as needed. Political boundaries should also be considered: if the goal is to guide management, then it may not be relevant for the footprint of SES to cross into different jurisdictions.

In the absence of such features or existing schema, previous research may aid in estimating spatial boundaries for the SES of interest and prior knowledge may also give an understanding of the scales of influence of different variables or indicators (e.g., where people come from to fish an area). However, in cases where the boundaries are simply not clear, it may be necessary to set boundaries based on the extent of existing datasets, recognizing that this pragmatic approach may not reflect how the system is truly integrated within the full context of the land- and seascape.

3.2. Step 2. Identifying social-ecological variables of potential value

Identifying relevant variables is both critical and challenging when it comes to research and monitoring within SESs, even where formal SES analysis is not being carried out. For example, within fisheries management, stock assessments are considered the “gold standard” but when the survey data to produce such assessments is absent, there is still a reluctance to use data obtained through other methods (e.g., local knowledge) (Jones et al., 2024). Similarly, despite a push towards “ecosystem-based fisheries management,” the integration of multiple stocks and indicators into a single framework has been slow (Townsend et al., 2019). The SESF can guide variable selection through a well-established structure.

The SESF is multi-levelled, with tiers of defined variables, providing a framework by which researchers can formalize their data collection using a shared vocabulary (McGinnis and Ostrom, 2014) (Fig. 3). The first (highest) tier, as described by McGinnis and Ostrom (2014), contains:

- The Resource System (*RS*), which defines the “ecosystem” which generates resource outputs, such as a lake, woodland, or fishery (static or migratory).
- Resource Units (*RU*), which capture the resource itself, such as fish or timber.;
- Actors (*A*), defined as individuals or groups directly or indirectly utilizing or interacting with the system of interest.
- Governance Systems (*GS*), which reflects how (or if) the Resource System, Units, and Actors are managed and by whom.

These four variables are centered on and causally linked to the interactions (*I*) and outcomes (*O*) at the convergence of these variables. Feeding into this system are both the social, economic and political settings (*S*) and the related ecosystems (*ECO*) (McGinnis and Ostrom, 2014). The framework is iterative and not static, in that *I* is causally linked to *O* and this process in turn causes feedback loops which may alter the dynamics of each of the other variables (McGinnis and Ostrom, 2014). However, it may not be necessary (or possible) to integrate such feedbacks into the investigation, but simply recognizing that they exist (e.g., between fisheries landings, regulations, and economic markets) provides important insight when trying to understand fluid systems.

Each of the eight tier-one categories (*RS*, *RU*, *A*, *GS*, *I*, *O*, *S* and *ECO*) is populated by multiple tier-two variables which describe the characteristics of the corresponding tier-one variable. For example, spatial and temporal distribution (RU7) is nested within the tier-one Resource Unit category (del Mar Delgado-Serrano and Ramos, 2015). These tier-two variables are usually those that the investigator will directly measure, or indirectly characterize through (latent) indicators (Nagel and Partelow, 2022).

Which tier-two variables or indicators to be included within a study also depends on the specific objectives, questions or approaches of the researcher (Schlüter et al., 2014). Not all of these variables will be relevant to a specific question or objective and the final selection needs to be defined and justified by the researcher or the people in charge of the monitoring. For example, resource unit mobility (RU1) may be more important within a fishery system than for mangrove forests. Beyond jurisdictional boundaries, geospatial representation of government or non-government organisations (GS1 and GS2) or monitoring and sanctioning (GS8) would often be challenging (or even impossible) to apply. However, protected areas managed both governmentally and non-governmentally, for example, can be distinguished within a geospatial format. Socioeconomic attributes (A2) may have fine-scale representation for specific localities but would often need to be inferred from coarser data for large-scale analysis.

Therefore, to identify variables, we recommend both a backward and forward reasoning process (Schlüter et al., 2014). Here, an initial set of variables can be the starting point for reasoning (forward processing), but the relevant or available indicators for the research question can also be used to redefine the base tier-one or -two variables (backward reasoning). For example, one may wish to start from the perspective of optimizing fisheries landings, a tier-two variable that represents the tier-one quantity of a “Resource Unit.” Alternatively, one may wish to start from the broad perspective of “sustainable coastal management” which can then be enacted through identifying multiple “Resource Systems” that comprise coastlines, and variables that reflect the status and condition of these systems.

3.3. Step 3. Open-data search and acquisition

There are a wide variety of repositories, portals and other location types within which marine/coastal geospatial social-ecological data may be hosted. Sources such as Copernicus, the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) provide hundreds of data layers at varying resolutions and spatiotemporal scales, and tens of thousands of more local and regional monitoring programs exist at finer scales, as well as data reported in the primary literature. Some data, such as species distribution records, may occur at a hyperlocal (i.e., point) resolution, while environmental data is often provided in a gridded format such as the Network Common Data Form (netCDF) at spatial resolutions of 0.5° or finer. These datasets usually have long time series and large spatial scales, from regional to global coverage. This large-scale, continuous coverage is often achieved through reanalysis models based on a combination of station or survey observations and climate and/or ocean models.

The range of data supplied by different providers is extensive and may encompass ecological or social system indicators or a combination of both. Some providers, such as the Copernicus Marine Store and Climate Change Service, the ESA, and NASA Earth Data, hold predominantly ecological data (when viewed from an SES perspective) with a wide variety of indicators covered, including water temperatures at various vertical layers, air temperatures, wind speed, precipitation, snow or ice cover, water chemistry, and primary production (e.g., chlorophyll-*a*), often at daily or weekly intervals. These datasets are not always restricted to the near past: for example, the United States National Oceanic and Atmospheric Administration's (NOAA) Extended Reconstructed Sea Surface Temperature database provides global water temperature estimates beginning in the year 1854. Thematically specialized databases also exist: for example, NOAA Coral Reef Watch provides data relevant to coral systems globally, such as a widely-used index to determine thresholds of heat stress (Degree Heating Weeks, NOAA Coral Reef Watch, n.d.). Other databases, such as the Global Biodiversity Information Facility, provide data on the distribution of species globally that can be combined with environmental data streams to understand why species occupy their observed ranges. Some have attempted to aggregate and present integrated data layers, such as BioORACLE and the Ocean Health Index. While these databases generally provide information at lower resolutions (e.g., annual means), they also provide a convenient way to query and access multiple layers simultaneously that are already expressed at the same spatial and temporal scales. Global databases also exist for social and economic data, such as for fisheries and aquaculture (Food and Agriculture Organization of the United Nations, 2024), world population (and projections, United Nations, 2024) and socio-economic attributes. For example, Global Data Lab (GDL), household survey data from multiple providers is analyzed to produce geospatial human dimension data such as the Subnational Human Development Index (SHDI; globaldatalab.org, 2024).

While a full overview of all data providers is well beyond the scope and purpose of this paper, an overview of a selection of providers, repositories and data papers providing data pertinent to coastal research and management is provided in Table 1.

While we have focused on datasets with large spatial scales here, datasets on specific localities, countries and regions can also be relevant and can even help to validate the large-scale low-resolution data layers. Globally, there is an increasing number of organisations and providers of finer-scale datasets which often hold pre-processed geospatial data on indicators which cannot be accessed elsewhere. For example, the

Table 1
Examples of data providers, portals and repositories relevant to coastal social-ecological research or monitoring.

Source	Brief overview	Example indicators	Link/reference
Copernicus Marine Service (CMS)	The marine thematic information service of the Copernicus Programme providing data from satellite and in-situ measurements combined with numerical models.	Physical and geochemical water properties, snow and ice cover	https://marine.copernicus.eu; European Union-Copernicus Marine Service (2024b)
Copernicus Climate Change Service (C3S)	The climate thematic information service of the Copernicus Programme providing data on historical, current and projected future climate data.	Historical, current and projected future climate indicators	https://climate.copernicus.eu; European Union-Copernicus Marine Service (2024a)
European Space Agency (ESA) Climate Office	Satellite and in-situ observation data from the ESA missions, Copernicus Sentinels, ESA third-party missions and partners combined with numerical models.	Multiple datasets from a number of agency missions including CryoSat (ice cover and thickness), Soil Moisture and Ocean Salinity (SMOS; aquatic indicators) and PROBA-V (vegetation cover)	https://climate.esa.int; ESA Climate Office (2024)
NASA Earth Data	NASA earth observation data	Atmospheric, physical and geochemical water properties, sea level, spectroscopy, indicators for anthropogenic change, extreme weather and SDM outputs among others	https://www.earthdata.nasa.gov; NASA Earth Science Data Systems (2024)
World Bank Databank	Global development data at national, regional and global scales including socioeconomic and development indicators.	A diverse range of global development time-series indicators collected by the World Bank.	https://databank.worldbank.org/home; World Bank Group Development Data Group (DECDG), 2024
National Ocean and Atmospheric Administration (NOAA) Climate Data Online (CDO)	Datasets built from direct observations from in-situ measurements. Some global datasets, some restricted to the USA.	Sea surface temperature, wave data, past and present weather, precipitation and air temperature among others	https://www.ncei.noaa.gov/cdo-web/; NOAA (2024)
Global Data Lab (GDL)	Independent data and research centre based at the Nijmegen School of Management at Radboud University. They have developed global indicators and databases from a compilation of over 500 household surveys in low- and	Human Development Indices computed at a subnational level, household wealth and vulnerability to climate change indices	https://globaldatalab.org; globaldatalab.org (2024)

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Table 1 (*continued*)

Source	Brief overview	Example indicators	Link/reference
	middle-income countries.		
Marine Regions	Hosts marine, coastal and terrestrial boundary data from a number of providers which are made available as direct download in the form of shapefiles.	Maritime boundaries, sea areas, ecoregions and fishery regions, emission control areas, topography, country boundaries	https://www.marineregions.org; Flanders Marine Institute (2024)
Bio-Oracle	Provides data on 26 physical, biogeochemical and topographic indicators for present (for v3 present = average of the years 2000–2020) and future climate scenarios under future climate scenarios for the surface and benthic environments.	Temperature, salinity, pH, sea ice cover, photosynthetic available radiation and bathymetry among others	https://bio-oracle.org; Tyberghein et al. (2012); Assis et al. (2024)
Ocean Biodiversity Information System (OBIS)	Data clearing house with over 5000 datasets and 120 million presence records for numerous taxa globally. Partners with a number of organisations including GBIF (also given here). Part of the Intergovernmental Oceanographic Commission of the United Nations Education, Scientific and Cultural Organization (IOC-UNESCO).	Species occurrence records with associated metadata.	https://obis.org; OBIS (2024)
Pangaea	Archive and repository for georeferenced earth data including the marine and terrestrial environments as well as human dimensions and social data.	Thousands of uploaded datasets. All specific to monitoring and research programmes.	https://www.pangaea.de; Felden et al. (2023)
Global Biodiversity Information Facility (GBIF)	An international network of governments and organisations facilitating the sharing and standardization of species occurrence records derived from multiple sources including museum/herbarium specimens, DNA barcoding and direct observations.	Species occurrence records	https://www.gbif.org; GBIF.org (2024)
Global Resource Information Database Geneva (GRID-Geneva)	Partnership between UNEP, the Swiss Federal Office for the Environment and the University of Geneva. Process,	Platforms managed by GRID-Geneva support a range of indicators on, for example,	https://unepgrid.ch/en; (UNEP/GRID-Geneva, 2025)

Table 1 (*continued*)

Source	Brief overview	Example indicators	Link/reference
	generate and model remote sensing data and make some products publicly available on dedicated platforms.	environmental hotspots, risk from natural hazards and	
NASA Socioeconomic Data and Applications Centre (SEDAC)	A Distributed Active Archive Center (DAAC) of NASAs Earth Observing System Data and Information System (EOSDIS) run by the Center for International Earth Science Information Network (CIESEN) at Colombia University. Specialises in human interactions with and within the environment.	Many data collections on social data such as agriculture, land use, population, food security and poverty.	https://sedac.ciesin.columbia.edu; CIESEN (2024)
National Snow and Ice Data Center (NSIDC)	Part of the University of Colorado (CU) Boulder Cooperative Institute for Research in Environmental Sciences (CIRES)	Sea Ice and snow	https://nsidc.org/home; NSIDC (2024)
General Bathymetric Chart of the Oceans (GEBCO)	Non-profit organization jointly operated by the International Hydrographic Organization (IHO) and IOC-UNESCO. Utilises data from	Bathymetry	https://www.gebco.net; GEBCO Bathymetric Compilation Group 2023 (2023)
United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC)	Collaboration between UNEP and the WCMC charity.	Provides data from a number of research programmes and thematic areas and hosts a number of global geospatial datasets on seagrasses, saltmarshes, coral reefs and mangrove forests, among others.	https://www.unep-wcmc.org; UNEP-WCMC (2024)
Detection and threats of marine heatwaves (CAREHeat)	Consortium working to develop marine heatwave detection based on the work of Hobday et al. (2016), advance scientific knowledge and demonstrate the value of marine heatwave data to society. Led by the Consiglio Nazionale delle Ricerche (CNR) Institute of Marine Sciences (ISMAR).	Marine heatwave occurrence	https://careheat.org; CNR-ISMAR (2024)
LandMark	Indigenous and community lands platform. The platform provides data such as Indigenous community land maps and natural resource rights, concessions to	Percent of Indigenous and Community Lands, Indicators of the legal security of Indigenous and Community Land, Indigenous	https://www.landmarkmap.org; LandMark (2024)

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Table 1 (*continued*)

Source	Brief overview	Example indicators	Link/reference
	mining, forestry and other industries as well as options to overlay land cover, protected area and tree cover loss and gain.	Population per Country	

Western Indian Ocean Symphony portal provides over 80 social-ecological layers, many of which were specifically processed for the region (WIO Symphony, 2022). While WIO Symphony can be used as a portal for data access, it also provides marine spatial planning tools such as cumulative impact assessments based on the methodology presented in Halpern et al. (2008). Portals such as Tools4MSP, the INSPIRE-geoportal and MarCOSIO similarly provide social-ecological data, such as coastal ecosystem data, transport networks and vessel traffic, for the coastal and marine area of Europe (Tools4MSP and INSPIRE-geoportal) Southern Africa and the Indian Ocean (MarCOSIO), based on secondary data sources (Tools4MSP, 2022; Sibolla et al., 2023; European Commission, 2024). These tools can be invaluable for researchers or managers working in the region due to the ease of access to the data. The Tanzania Sensitivity Atlas (TanSEA) and Zanzibar Sensitivity Atlas (ZanSEA) provided data on multiple critical indicators across Tanzania and Zanzibar, such as point records on aquaculture and mariculture, but are no longer accessible, with outdated links and server issues. This data may now be dated but could provide value if looking to explore change over time. This highlights the importance of hosting critical data within infrastructures which are both accessible now and into the future, so as not to lose valuable historic data.

Another benefit of hosting data on centralized servers is that specific application programming interfaces (APIs) can be developed to promote accessibility through various softwares, including open-source platforms such as the R programming language. For example, packages exist to explore databases like the World Register of Marine Species (https://www.rdocumentation.org/packages/worrms/) and FishBase (https://www.rdocumentation.org/packages/rfishbase/versions/4.1.2). In this way, pipelines to query, acquire, and curate relevant data (e.g. on organism traits) can be implemented into reproducible scripts. Another noteworthy platform is ERDDAP, or Environmental Research Division's Data Access Program, maintained by NOAA. This is a data server that streamlines different datasets into standardized formats that can be accessed through a common interface. Servers can be maintained by any organization and serve any kind of gridded and tabular data and can even express the data as an image (e.g., map, National Oceanographic and Atmospheric Division, n.d.).

Many additional indicators can be gleaned from published works and data papers. For example, Yeager et al. (2017) provide a social-ecological dataset for the marine environment including human population and land area within different radii of each marine grid cell, alongside net primary productivity, distance to provincial capital and wave energy. The trend towards FAIR data principles in research is not new, but the move to many journal publishers requiring the publication of data sources has opened new avenues by which to acquire previously hard-to-access indicators. The growth in social-ecological thinking has also led to the development and publishing of data sources specifically for this purpose. However, while many of these sources may provide valuable indicators, pre-processed layers provided may lose value over time. For example, Yeager et al. (2017) is now outdated and the values for population density would be superseded by new sources. Such questions need to be considered with care during data collection and will, in part, inform the setting of temporal boundaries in step 1.

3.4. Step 4. Data exploration, processing and cleaning

Prior to use, downloaded data needs to be explored to ensure data quality as well as adequate coverage. Databases relying on observations from individuals, organisations, and surveys may hold erroneous or suspect data which needs to be investigated and cleaned. Such datasets usually have methods of flagging outliers or data with known or potential issues. The use of the metadata is vital in identifying potential sources of errors. For example, taxonomic names may change over time, methodologies may differ between surveys and observations may be based on direct observation, genetic data, or dead and/or fossil records. Harmonization of taxonomies is challenging with discrepancies associated with misspellings within databases, use of synonyms or abbreviations which could lead to either missing or erroneous data points for species distributions and impact spatial and/or temporal analysis (Zermoglio et al., 2016; Freitas et al., 2020). It is likely that suspect data will need to be removed prior to analysis or compared to a centralized database, for example, the World Register of Marine Species. See Grenié et al. (2023) for an example of an additional workflow for the harmonization of data indexed by taxonomy. It is critical that any processing be well-documented so it is abundantly clear how the data were treated, including justification for removing or editing any data points, to promote reproducibility and future applications. Open-source scripts in a programming language, such as R, can provide long-term records of not just the data sources, but also the treatment of the data before it is used in the SESF.

For gridded data layers, whether a grid cell is classified as marine or terrestrial usually depends on the cover at the midpoint of the cell. Coastal data coverage is also complicated by factors such as turbidity in the near-shore environment impacting models, whose assumptions are usually based on open-water conditions (Ouellette and Getinet, 2016). Due to this, geospatial climate and physical data coverage in the coastal zone is often sparse or patchy. Techniques such as Ordinary-Kriging (OK) could be performed as a gap-filling tool for the irregular coastal coverage, as described by Kostopoulou (2021). This would require the conversion of the downloaded gridded data to point data and a normalization (e.g. logarithmic transformation), if required, of the dataset. This data can then be analyzed with geostatistical tools which can model the distribution of data. These models can then be used in an OK process for interpolating missing values (Kostopoulou, 2021). The need for this procedure would be dependent on the requirements of the dataset from the user. Such interpolations could be validated against or adjusted (e.g., using an offset value) given in situ measurements taken by the investigator or other monitoring organisations (see Step 5a).

3.5. Step 5a and 5b. Planning for in-situ data collection, add value to already collected data or use standalone

Prioritizing data collection depends on a combination of the question being asked and what is already known and unknown about the system. We need to understand the knowledge gaps, or the “known unknowns” (Paterson et al., 2021). Once the final set of indicators has been defined, we can better understand what data can and should be prioritized when it comes to future data collection in the field. The SESF which aided in the initial exploration of potential open, geospatial data can be re-employed to cross-reference the newly acquired open dataset and identify gaps in coverage which would be important for answering stated research questions and aims. Where resources are limited, harnessing open data may aid in optimizing time, finances, and carbon footprint towards collecting data on known unknowns. Additionally, it is also important to plan for what may or may not need field validation. For example, with multiple temperature datasets, there may be value in sampling temperatures to validate the gathered geospatial datasets and or guide data adjustment.

In many cases, primary data collection may not be necessary, or it may be that fieldwork has already taken place and further data needs have been identified. Alternatively, it may be that the study is entirely desk-based, using existing data sources. Indeed, many SES studies are carried out relying solely on secondary data sources (Nagel and Partelow, 2022). The workflow outlined here provides a tool whereby social-ecological data can be collected to expand on those variables more frequently gathered within primary data collection. Biological and geophysical FAIR geospatial data is comparatively frequently leveraged within research, such as species distribution and other modeling approaches. The importance of harnessing social data within studies has been acknowledged for some time, however, there has been a perceived lack of availability of relevant data (Cornu et al., 2014). To facilitate the application of human-dimensions and other social data within research, data should be easy to access and use.

Here, we show how applying the SESF within a formalised search for relevant, open geospatial data can lay the groundwork for expanding on the data sources, indicators and variables applied in research. While no previously generated dataset will be entirely “fit-to-purpose,” open data can be leveraged and expanded upon to improve the scope and quality of the investigation, minimize costs, and promote efficiency.

3.6. *A demonstration of the framework for Indo-Pacific seagrass systems*

To clarify the steps described, we apply our workflow to a model seagrass system. Seagrass meadows are a widespread coastal system, the importance of which, to maintaining healthy coastlines and sustaining coastal communities, is increasingly recognized (Orth et al., 2006). Globally their conservation contributes to achieving 16 out of the 17 United Nations Sustainable Development Goals (Unsworth et al., 2022). In this case, we focus on the Indo-Pacific region where seagrasses are directly linked with human well-being (Jones et al., 2022b). We are using a generic example of one or more sites across the region positioning ourselves as either researchers or managers.

3.6.1. *Step 1. Defining questions and system boundaries*

In laying out potential questions and system boundaries (Step 1), we propose several generic lines of inquiry. For example, we might wish to investigate the primary drivers of change in seagrass cover or we may wish to understand how management, such as protection, affect the seagrass resource and also fisheries exploitation by the local community.

In this example, the boundary is defined by the Tropical Indo-Pacific biogeographic zone (Short et al., 2007), encompassing the region from the eastern coast of Africa to the eastern Pacific and extends from Southern Japan to Southern Mozambique (Fig. 2). The region is the most diverse of the six seagrass bioregions, with 24 species of seagrasses present (Short et al., 2007). In further defining the boundary we also set a temporal limit for our data search. It was assumed that data since the year 2020 would be less available than that prior to that year due to the time often taken in processing and publishing data layers and the impact of the global COVID-19 pandemic on data collection. As we also wanted to have a recent perspective on the region, we constrained our search to data from the period 2010–2020.

3.6.2. *Step 2. Identifying social-ecological variables of potential value*

Using the SESF, we identified potential tier-two variables: for example, RU5 – number of units, A1 – number of relevant actors, and S1 – Economic development, that address our questions around potential drivers of change and impacts on seagrass-associated services. These tier-two variables fall across all the tier-one categories of the SESF describing both the social and ecological systems; the Resource Units (RU); Resources System (RS); Actors (A) and Governance System (GS); Related Ecosystems (ECO) and Social, Economic and Political Settings (S). TO a lesser extent, Interactions (I) and Outcomes (O) are also included.

3.6.3. *Step 3. Open-data search and acquisition*

Once SES variables were identified, we conducted a broad survey of open coastal data to identify putative indicators. Following the backward-forward reasoning process of Schlüter et al. (2014), we identified additional indicators that we were initially unaware of or for which we did not expect to source data leaving us with indicators for 20 tier-two variables. In some cases, the same indicator was provided by numerous data sources. Clearly, additional processing is necessary.

3.6.4. *Step 4. Data exploration, processing and cleaning*

We explored and quality-checked the data obtained throughout the search using Quantum GIS (QGIS; version 3.28.0-Firenze) (examples given in Fig. 3). As can be seen in Fig. 3, there is a disparity in resolution and there are multiple data types being brought in, including gridded raster data, points and polygon layers. We checked the coverage in the coastal zone and observed considerable patchiness near the coastline which could be interpolated as necessary. How this patchiness would be dealt with for analysis would be dependent on the user needs. Due to the

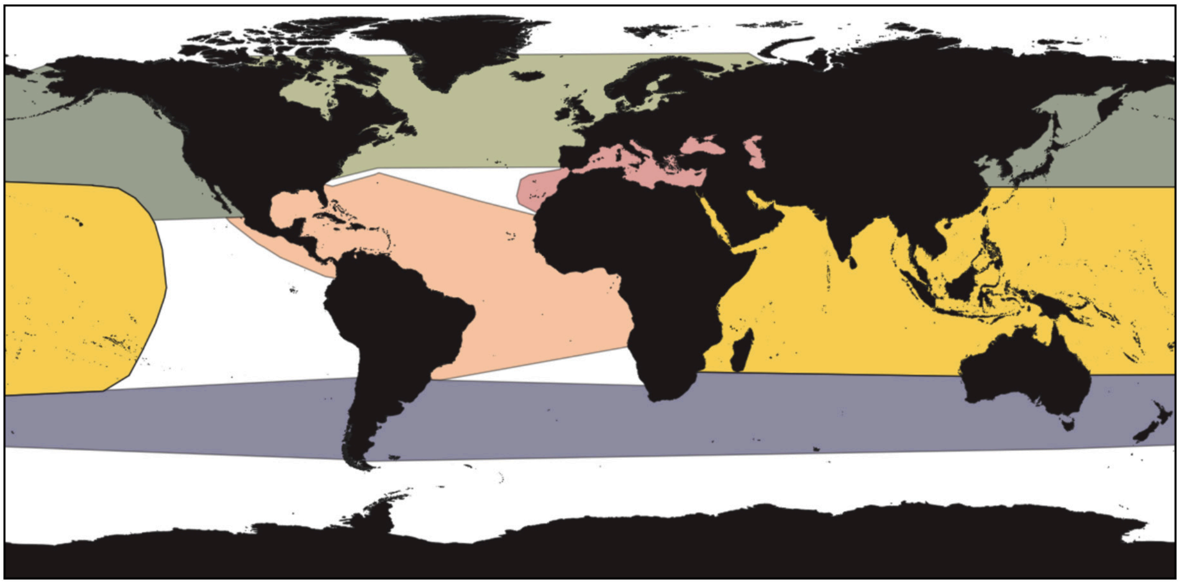

Fig. 2. Map of the six seagrass bioregions defined by Short et al. (2007). The Tropical Indo-Pacific is shown in yellow. Bioregion shapefiles retrieved from code and data from (Dunic et al., 2021). Seagrass distribution, shown in green, from UNEP-WCMC and Short (2021) point records.

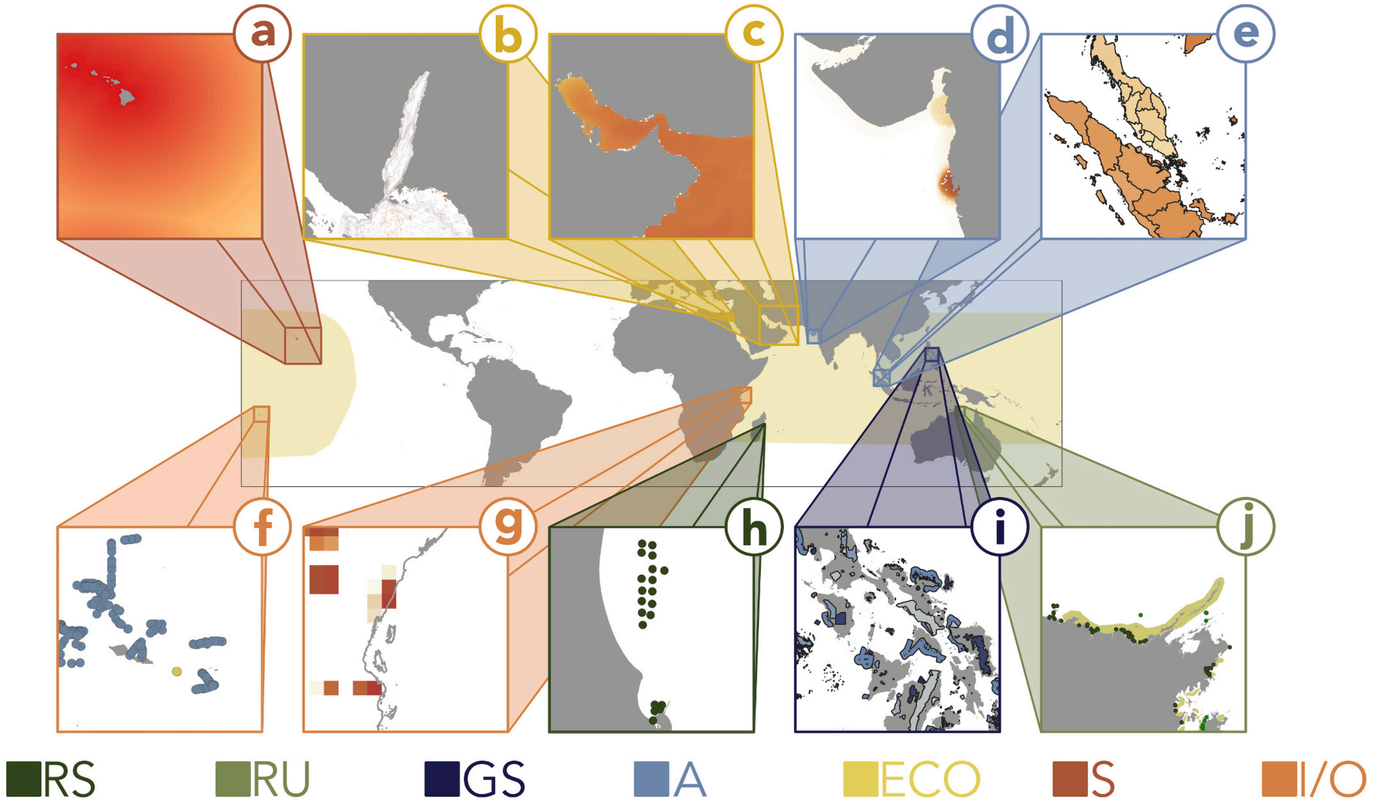

Fig. 3. Samples of open geospatial data identified for Indo-Pacific seagrasses: a) distance to port; b) bathymetry; c) water surface temperature for 31/12/2023; d) human population density within 50 km for the year 2020; e) subnational human development index; f) fishing effort by flag for 31/12/2020; g) threat of urban expansion; h) named anchorages for 06/12/2022; I) terrestrial and marine protected areas and OECMs for February 2024; j) seagrass distribution point and polygon records from 4 datasets. Color codes correspond with the SESF tier-one variables: RS) Resource System (dark green); RU) Resource Units (light green); GS) Governance System (dark blue); A) Actors (light blue); ECO) Related Ecosystems (yellow); S) Social, economic and political settings (red); I/O) Interactions/Outcomes (orange).

desire for coverage up to the shoreline throughout the Indo-Pacific region, it may be beneficial to further process the geospatial layers to remove gaps using a technique such as Ordinary-Kriging.

Following the exploration and cleaning of the data, we narrowed our selection to 53 unique indicators from 82 sources which had adequate spatial and temporal scales, resolutions and coverage (Fig. 4). A full description of these is provided in Appendix A. In this example, we didn't exclude any sources based on this part of the workflow. This is partly down to the fact that we retained patchy data which we felt could be interpolated and gap-filled, but is partly also down to the scale at which we looked for data, with larger scale datasets often having greater spatial and temporal resolutions. For higher-resolution studies we would expect fewer sources to match our criteria.

3.6.5. *Step 5a & 5b. Planning for in-situ data collection, add value to already collected data or use standalone*

With the data gathered through steps 1 to 4, the final dataset could be applied within existing research or monitoring programmes (Step 5a) to, for example, identify drivers of change in Indo-Pacific seagrass meadows or the impacts of protection on the seagrass SES. Another exercise could identify potential knowledge gaps in a specific SES and guide future primary data collection in the region (Step 5b). For example, our dataset provides some information on the numbers of potential actors within seagrass SESs, along with information on distances to markets. However, the proxy for distance to market is given as distance to regional capital rather than where local markets are situated. Such high-resolution data would be necessary for fine-scale analysis, for example when looking at specific seagrass meadows and associated fishing pressure.

Following this framework has proved to be an enlightening process for us. The exercise of compiling the database alone has made our research team, which includes many seagrass scientists, aware of relevant data and stimulated potentially addressable research questions to be pursued. Through sharpening our understanding of the availability of open-geospatial data relevant to Tropical Indo-Pacific seagrass SES, we have increased our understanding of the data available to us in our own work and plan to use this process to supplement and inform both primary data collection as well as desk based studies.

4. Conclusions

We set out to investigate the extent to which the social-ecological system framework can serve as a vehicle for identifying critical open data necessary for a coupled social-ecological understanding of coastal ecosystems. We present a workflow for integrating both ecological and social system geospatial data in coastal system research using open data and demonstrate this using an example of Tropical Indo-Pacific seagrass SES. In doing so, we highlight the extensive availability of data corresponding to a broad range of SESF variables which can be harnessed by users across a range of systems. The increasing availability and quality of open geospatial data present significant opportunities for advancing coastal science by making researchers aware of the broader context of the system(s) in which they are working and facilitating exploration of novel questions.

There is a recognized need to better integrate social and ecological variables into SES research (Rissman and Gillon, 2017; Guerrero et al., 2018). Where resources are limited, for example where interdisciplinary teams are unavailable or where time and financial restraints limit the scope of primary data collection, open-data offers a compromise in

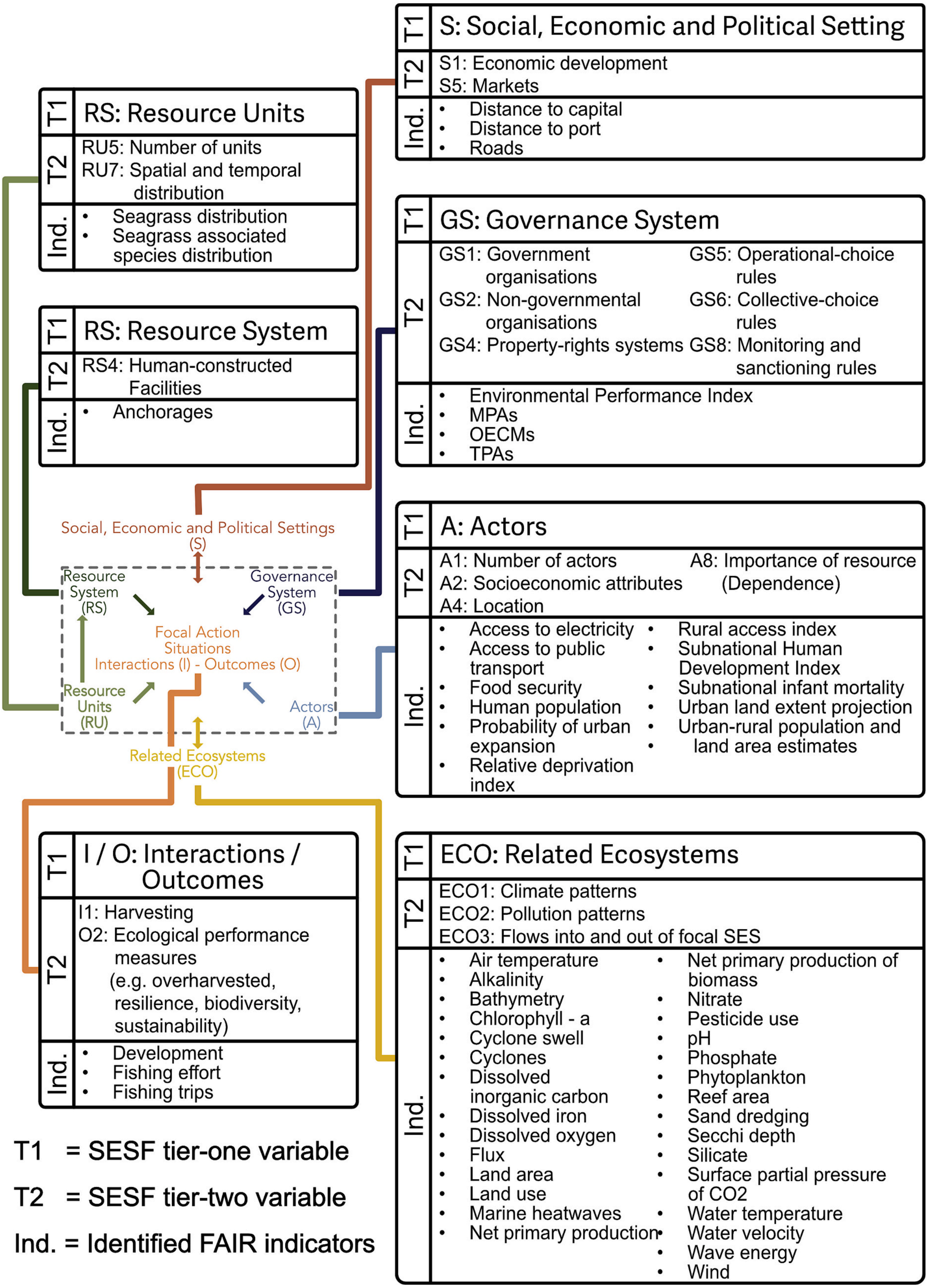

Fig. 4. Overview of open geospatial indicators (Ind.) identified for Indo-Pacific social-ecological systems. Boxes show the tier-one (T1), tier-2 (T2) SESF variables for which subsequent indicators were found. Identified indicators may correspond with one or more T2 variables.

broadening the range of social-ecological data incorporated into analysis, management or monitoring programmes. Within coastal research, there is increasing adoption of social-ecological approaches to answering complex problems in resource management, along with many examples of open, social-ecological data being used across different coastal systems, research questions and applications (e.g. Cinner et al., 2013; Hagger et al., 2022; WIO Symphony, 2022). Numerous resources, databases and repositories hold a wide array of data pertinent to this field, a selection which have been presented within this paper. But with this growing array of data comes an ever-increasing hurdle to users, with regard to identifying what is relevant to them and how this data may fit into a wider system perspective. This "paradox of choice" has the potential to paralyze those who are overwhelmed by the litany of databases and indicators that could be made relevant to their questions.

Some of the challenges of the open-data revolution, as highlighted by Salguero-Gómez et al. (2021), include the harmonization of datasets, biases within data, the expertise required in effectively interrogating this data and communication, including regarding the accreditation of data providers. Some of these issues can be observed within the data compiled within this case study. For example, biases in data availability are clearly seen here, with extensive biogeophysical data sources, but limited data on interactions which may be occurring within seagrass meadows, limited to industrial fishing activities. No long-term monitoring geospatial datasets were identified within the repositories used within this paper and much of this data remains guarded. The expertise requirement of data users is also a barrier which should be mitigated through better tools and training. There is, of course, work to be done on enhancing these datasets. As seen in the dataset compiled here, there are gaps, some data is coarsely aggregated and there are sometimes uncertainties on the accuracy. In particular, the spatio-temporal ranges variation between datasets and patchiness of some data products create some hurdles which may require careful consideration depending on the aims of the research or monitoring. However, as a tool for developing a holistic perspective on coastal systems, these datasets have a unique potential for bridging disciplinary divides and providing critical social and ecological indicators for research and management. While the data highlighted within this paper should be largely seen as indicative of true values (with remote sensing and modeling approaches inherently producing best estimates of conditions over space and time), it can provide useful indicators for multiple SESF variables to enhance overall system understanding.

It is important to note that these repositories do not just provide data but accept it as well. Contributing data to, for example, the Ocean Biodiversity Information System (OBIS), the Ocean Data Information System (ODIS), or other open-access data and information clearinghouses and federated systems that use common conventions to share and exchange their (meta)data would greatly support accessibility for potential users. In turn, data can be more widely used and applied, increasing its long-term value and return on investment. By making data (and metadata) available, primary data generators can facilitate broad-scale social-ecological investigations and create an inclusive and supportive global community. It is crucial that we enhance our engagement with these repositories and opportunities, share their potential, and build expertise within our respective academic and non-academic communities. Such changes may necessitate rethinking the current etiquette around how open-data is used within publications including, but not limited to, the citation of the data collector, encouraging and incentivizing efforts in data collection and sharing (Salguero-Gómez et al., 2021).

The Social-Ecological System Framework (SESF) provided a useful theoretical framework on which to build the data-search in the workflow in this paper. The SESF can be a valuable tool in identifying relevant variables and guiding research methodologies and its application can help structure comprehensive analyses that include a broad range of social-ecological factors. The use of the SESF here, even in its most basic function as a categorisation of variables within a unified framework and common vocabulary, demonstrates the power of harnessing these frameworks within and outside of environmental science. Leveraging open data and comprehensive frameworks like the SESF, researchers and policymakers can better understand and predict changes in coastal environments. This understanding is essential for developing strategies that ensure the sustainable provision of ecosystem services.

CRediT authorship contribution statement

Nicholas M. Hoad: Conceptualization, Methodology, Writing – original draft. **Jonathan S. Lefcheck:** Writing – review & editing. **Nikolaos Alexandridis:** Writing – review & editing. **Benjamin L.H. Jones:** Writing – review & editing. **Johan S. Eklöf:** Writing – review & editing. **Lina Mtwana Nordlund:** Supervision, Funding acquisition, Writing – original draft, Methodology, Conceptualization, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180276.

Data availability

The data sources used within this article have been outlined within the supplementary material.

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